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## **An ontology-based approach for bank stress testing**

Yan, Jiaqi ; Hu, Daning ; Zhao, Leon

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# An Ontology-based Approach for Bank Stress Testing

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## Abstract

*The 2008 banking crisis has demonstrated that there is the lack of effective methods for modeling and analyzing “exceptional but plausible” risk scenarios in bank stress testing. However, existing bank stress testing practices mainly focus on modeling probability-based risk factors and events in a “static snapshot” of the banking systems, but largely ignore the dynamic processes in which financial crisis events and their interactions creates various complex risk scenarios. In addition, the rare (low probability) risk events such as the bankruptcy of Lehman Brothers that can cause “exceptional but plausible” crisis scenarios are largely ignored due to the lack of appropriate modeling and analysis methods. To address this problem, we developed an approach called Banking Event-driven Scenario-oriented Stress Testing (or simply the BESST) which mainly includes three components: 1) a set of stress testing ontologies; 2) an event-driven scenario model (OESM); and 3) a scenario recommendation component. In addition, we show how to use BESST to model and examine “exceptional but plausible” stress testing scenarios in an example process of crisis events. In general, this research has provided the bank stress testing stakeholders a novel approach for modeling and analyzing the rare risk events and their dynamic processes in various financial crisis scenarios.*

## 1. Introduction

The recent 2008 global financial tsunami has pushed the banking system to the brink of a system-wide collapse. One of the major causes of this crisis is that the financial stakeholders, including the big banks and regulators, failed to effectively model and calibrate the “exceptional but plausible” scenarios in bank stress testing, in which rare macroeconomic events may cause contagious bank failures and lead to the breakdown of a banking system [1]. These crisis scenarios contain complex events of large magnitudes and impacts on banking systems that are often very

rare (e.g., the bankruptcy of Lehman Brothers). Such highly important events that are beyond the realm of normal expectations are called as “Black Swan” events [2]. The 2008 financial tsunami and the recent Euro debt crisis have demonstrated that modeling and analyzing such “Black Swan” events in bank stress testing is critical for the stability of the global banking system.

However, there are two major challenges in effectively modeling and analyzing stress testing scenarios that contains such exceptional but plausible events. First, the rarity of “Black Swan” events and the complexity how they interact with each other in dynamic event processes made it very difficult to model using traditional probability-based modeling approach which models various financial risk factors in a static “snapshot”. These probability-based methods such as the Value at Risk measure [3] mainly focused on evaluating the vulnerability of the banking system to single risk factors, or just combining the analysis of multiple risk factors into a single estimation of the probability distribution of a bank’s aggregate losses. However, real-world financial crisis scenarios are often driven by various “Black Swan” events and their interactions in dynamic event processes. Therefore, an event-based approach is needed to model the full dynamics of such dynamic risk event processes in stress testing scenarios.

Second, the imaginative capabilities of stress testing scenario designers often are limited since “Black Swan” events are too rare to imagine. For example, the European Banking Authority in 2009, 2010 designed the stress testing scenarios by assuming there is a relatively small -0.6% economic growth in the Euro area. However, in 2011 it was clear that such assumptions were not only just plausible but were certain to happen. They have to redesigned the scenarios by assuming a -4.0% growth scenario. Therefore, effective decision support methods such as scenario recommendation mechanisms are needed to support stress testing scenario designers for designing all possible scenarios, including those rare “Black Swan” events. Moreover, the recommended scenarios also need to be checked against completeness and

soundness, in order to ensure 1) all the possible “exceptional” scenarios are recommended, and 2) all recommended scenarios are “plausible”.

To address the above challenges, we developed a novel approach called Banking Event-driven Scenario-oriented Stress Testing (or simply the BESST) which mainly includes three components: 1) a set of stress testing ontologies; 2) an event-driven scenario model (OESM); and 3) a scenario recommendation component. To the best of our knowledge, our research is the first to study how to model bank stress testing scenarios from a non-probability event-driven perspective. More specifically, BESST provides bank stress testing stakeholders (i.e., bankers and regulators) an alternative approach for modeling “Black Swan” events and their dynamic event processes that probability-based modeling approaches failed to capture.

The remainder of this paper is organized as follows. In the second section, we provide a review of related studies. The third section describes the overview of the proposed BESST approach. The fourth and the fifth section describe BESST in detail. At last, we discuss the research contributions and suggest directions for future work.

## 2. Related Studies

Sorge and Virolainen [4] reviewed existing stress testing modeling methodologies and proposed a schematic classification. This classification categories stress testing methods into two types: the piecewise approach, and the integrated approach. The piecewise approach studies the direct linear relationships between macro-economic variables (e.g., interest rates) and certain financial risk indicators (e.g., capital adequacy ratio and return on equity). The estimated coefficients from the linear regression are used to predict the impacts of possible adverse economic scenarios on the banks’ financial risk indicators.

Thus the piecewise approach actually models an individual stress scenario as a combination of a specific set of macro fundamental variables. For instance, Kalirai and Scheicher [5] models the aggregate loan loss provisions in the Austrian banking system as a function of set of macroeconomic variables which include general economic indicators such as GDP, CPI inflation, and income, consumption and investment in the household and corporate sectors. Hoggarth et al. [6] focused on the relationship between banks’ loan write-offs and the UK output gap, retail and house price inflation, and the nominal short-term interest rate. Moreover, Saurina and Delgado [7] studied the relationship between loan loss provisions

and a set of macroeconomic indicators which includes unemployment rate, interest rates and indebtedness.

The piecewise approach is very intuitive and its computational cost is usually low since these models are often in linear functional forms. However, in general there is lack of empirical proofs for the validity of such linear relationships in past financial crises. Relationships among risk factors in real world financial crisis scenarios are often much more complex than the linear relationship assumption in the piece-wise approach.

The integrated approach takes a further step to integrate the analysis of banks’ vulnerabilities to multiple risk factors into a single estimate of the probability distribution of banks’ losses under a stress scenario. This approach combines analysis of multiple risk factors into a single distribution and models nonlinear effects of economic shocks on banks. The integrated approach differs from the piecewise approach mainly from two perspectives: 1) it focuses on integrating the analysis of banks’ market and credit risk factors rather than several single financial risk indicators; 2) it enables researchers to model the non-linear relationships between the macroeconomic factors and possible bank losses, as opposed to just modeling the direct linear relationships like the piece-wise approach did.

However, both piecewise and integrated approaches are limited in terms of their fundamental assumptions. First, both approaches assumed that a scenario is “static” and all changes in macro fundamental variables happens at the same time and will not change during the course of study. But in reality changes in risk factors are triggered by events or organizations’ behaviors (e.g., Fed raises interest rate aiming to reduce inflation). And these events and behaviors can happen in different sequences and thus have different impacts on the stability of banking systems. In other words, these two approaches lack the ability to model and analyze the dynamics of risk event processes in financial crisis scenarios for stress testing.

Second, people who design stress testing scenarios are often limited by their imaginative capacities and fail to imagine exceptional but plausible future scenarios. Sometimes it is because bank risk management professionals and researchers largely rely on probability-based financial risk management techniques and cannot imagine (believe) events with extremely small chances (e.g., the “Black Swan” events). Sometimes it is just that people do not possess the comprehensive deductive capabilities like computers do in predicting all possible stress testing scenarios. Therefore, there is a lack of automatic methods to support stress testing designers in terms of

modeling all possible financial crisis scenarios, including the exceptional but plausible ones.

In addition, similar with the imaginative capabilities, people often lack the capabilities to ensure the plausibility of the complex crisis scenarios they designed, simply because there are too many complex risk events and factors to consider with human deduction abilities. An effective automatic deduction mechanism is needed to ensure the plausibility of the financial crisis scenarios imagined by stress testing designers.

### 3. Banking Event-driven Scenario-oriented Stress Testing (BESST)

To address the research challenges summarized in Section 2, we proposed a novel approach called Banking Event-driven Scenario-oriented Stress Testing (BESST) based on a set of proposed ontology. Figure 1 shows the overview of the BESST approach which mainly consists of two components: 1) an ontology-supported scenario model (OSSM), and 2) an algorithm for recommending all possible scenarios that are plausible.

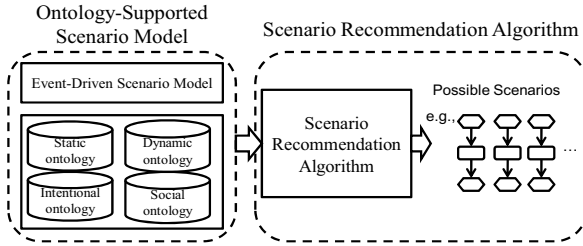


Figure 1. Overview of BESST Approach

OSSM is composed of an event-driven scenario model and a set of bank stress testing ontologies. The event-driven scenario model defines the risk events, the bank activities, as well as the rules that govern their evolvement. The event driven scenario model provides the basic methods to modeling a stress testing scenario. The four types of bank stress testing ontologies provide formal representations of the concepts and rules used in the stress testing scenario modeling, as well as a foundation for logic deduction which enables the scenario recommendation function. We will introduce the details of the proposed BESST approach in the following sections.

## 4. Ontology-Supported Scenario Modeling

### 4.1. Event-Driven Scenario Model

The event-driven scenario model aims to define the basic elements of a stress testing scenario. A stress testing scenario consists of a sequence of organization (e.g., bank) activities and risk events. The risk event asserts and represents the facts of economic situations determined by the economic proposition at a specific time point. An **economic proposition** is a term or formula written in first-order logic to describe the status of economic resources (e.g., low (interest\_rate), high (inflation rate)). An economic proposition is **plausible** when it can be reasoned with “capability” and “rationality”, in other words, the economic resources can reach a status because some actor has the capability to manipulate this economic resources into this status and the actor has an intention to do so. For example, interest rate now is low because Fed Reserve has the capability to manipulate the interest rate and it lowers the interest rate intentionally.

An **event**  $e$  is a time point where some economic propositions  $\phi$  about economic resources hold true.

#### Definition 1: Event

An event is a 3-tuple  $e = \langle t, R, P \rangle$ , where  $t$  is a time point,  $R = \{r \mid r \text{ is an economic resource in the scenario}\}$ ,  $P = \{P(e, r): \{\phi(r)\} \rightarrow \{\text{true, false}\}, r \in R\}$  is the set of truth assignment to the economic propositions  $\{\phi(r)\}$  at each event.

Events are linked by activities. An activity corresponds to a task executed by some actors in the scenario, the happening of which will trigger the appearance of a new event.

#### Definition 2: Activity

An activity is a 3-tuple  $\langle \text{aid}, \text{ag}, \text{t} \rangle$ , where aid is the unique identifier of the activity; ag is the actor that carries out the task, t is the task that is carried out.

In order to express the dynamics of the stress-testing scenario, we assume that the scenario consists of a set of possible events. Each event occurs at a particulate time. One of these events represents “testing now”, the “happened past” consists of a linear discrete sequence of events occurring at the time before “now”, and the “happen in future” consists of a linear discrete sequence of events occurring at the time after “now”. To express the temporal properties at each sequence of events, we incorporate a set of modal connectives.  $\diamond$  means sometimes, and thus  $\diamond\phi$  is satisfied now if  $\phi$  is satisfied either now or at some future event; and  $\circ$  means next, and thus  $\circ\phi$  is satisfied now if  $\phi$  is satisfied at the next event.

#### Definition 3: Event-Driven Scenario

An event driven scenario is defined to be a tuple  $s = \langle E, A, L \rangle$ , where  $E$  is the set of events in the scenario,  $A$  is the set of activities in the scenario;  $L = \{\text{next}(x, y) \mid x, y \in A \cup E\}$  is the set of relations on the events and activities.



#### Events

E0: Inflation

E1: Federal funds rate are increased

E2: lending rates are increased

E3: unemployment rate is increased

#### Activities

A1: Fed raises federal funds rate

A2: commercial bank raises lending rates

A3: manufacturer reduces investments

**Figure 2. An Event-Driven Scenario**

Figure 2 shows an example of event-driven scenario. Let's assume the time point of E1 is now. E0 has happened in past, E2 is going to happen next, and E3 are going to happen in future. Therefore, economic propositions of  $\diamond \text{increased}(\text{lending\_rates})$  and  $\diamond \text{increased}(\text{unemployment\_rate})$  are satisfied at the event now.

## 4.2. Bank Stress Testing Ontologies

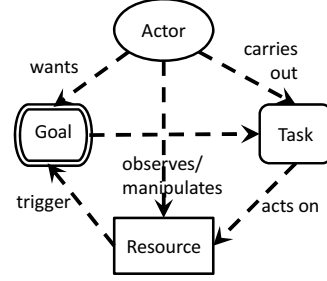
In order to construct “exceptional but plausible” events, we developed a set of stress testing ontologies to better understand the plausibility of various risk events (Definition 10). This set of ontologies is used to support the event and process modeling in stress testing scenarios and effectively enables the scenario recommendation function of BESST approach.

#### Definition 9: Ontology

An ontology is defined to be a set of constraints, which declare the entities and entities' relationships in the stress testing scenario,  $O = \{c \mid c \text{ is a constraint declaring the entities and their relationships}\}$ .

To develop the ontology, we first propose four meta-classes: Actor Class, Goal Class, Task Class, and Resource Class as shown in Figure 3. Every entity in the domain can be an instance of these meta-classes.

- Actor, which models a financial institution that has strategic goals, possesses resources, and intentionally acts according to the principle of rationality within the system or the organizational setting.
- Resource, which represents the material or information an actor observes/manipulates. The description of the resource's status forms an economic proposition.
- Task, which represents a way of doing something at an abstract level. The execution of a task (i.e., activity) can be a means of satisfying a goal.
- Goal, which represents an actor's strategic interests, refers to the actor's desire state.



**Figure 3. Relations between Meta Classes**

Given these four meta-classes, we can have the formal definition of the plausibility of an economic proposition.

#### Definition 10: Plausibility of economic proposition

An economic proposition  $\phi(\text{resource})$  ( $\text{resource} \in \text{Resource}$ ) is defined to be plausible, iff  $\exists a \in \text{Actor}, \exists t \in \text{Task}, \exists g \in \text{Goal}, (a, t) \Rightarrow \phi(r), (a, g) \Rightarrow (a, t)$ .

A stress testing scenario is defined to be plausible if all of the economic propositions in the scenario are plausible.

In this research, we adopted the ontology framework developed by Jurisica et al. [8] for meeting knowledge management needs (i.e., knowledge representation and logical deductions) from an information systems perspective. This framework consists of four broad ontological categories, which, respectively, deal with *static*, *dynamic*, *intentional* and *social* aspects of the world. It was suggested that for a wide range of real-world applications, the representations of relevant knowledge can be built based on the primitive concepts derived from these four ontological categories. These ontologies have been widely used for knowledge management purposes [9] and proved to be effective in supporting risk management in financial and banking domain [10, 11]. These ontologies can be specified as constraint metadata as defined below.

#### Definition 11: Constraint metadata

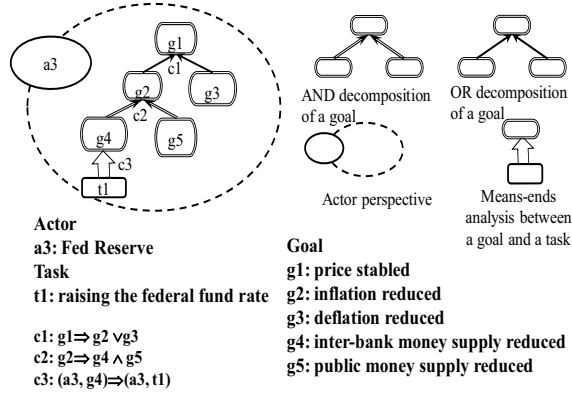
For each constraint  $c \in O$ , its metadata is defined as a five tuple  $\langle \text{cid}, \text{TY}, \text{P}, \text{H}, \text{MC} \rangle$ , where cid is the unique identifier of the constraint.  $\text{TY} \in \{\text{static ontology, intentional ontology, dynamic ontology, social ontology}\}$ , P is the premise of the constraint, H is the conclusion of the constraint,  $\text{MC} = \{\text{mc} \mid \text{mc} \in \text{Actor} \cup \text{Task} \cup \text{Resource} \cup \text{Goal}\}$ .

For example, c1 ( $c1: g1 \Rightarrow g2 \vee g3$ ) is a constraint meaning that if g1 (i.e., goal NO.1) exist, then either g2 or g3 exist. Here, 'c1' is the unique identifier cid of this constrain; c1.TY means the ontology type of the underlying constraint c (i.e., Intentional Ontology);

$c1.H = "g2 \vee g3"$ , as the head of the constraint, is inference by the premise of the constraint  $c1.P = "g1"$ .

#### 4.2.1. Intentional ontology

Intentional ontology models the actors' (e.g., financial institutions) motivations – what the actor desires or intends to do. For example, Fed Reserve (represented as  $a1$ )'s goal can be graphic represented in. The goals can further break down into sub-goals by AND/OR decompositions. For instance, the goal of stable price (represented as  $g1$ ) can be decomposed into reducing inflation (represented as  $g2$ ) or reduce deflation (represented as  $g3$ ), which can be represented by constraint  $c1$ ; the goal of reduce inflation ( $g2$ ) can be further decomposed into reduce inter-bank money supply ( $g4$ ) and reduce public money supply ( $g5$ ). This graphic representation can further be represented as constraint  $c1$  and  $c2$ .

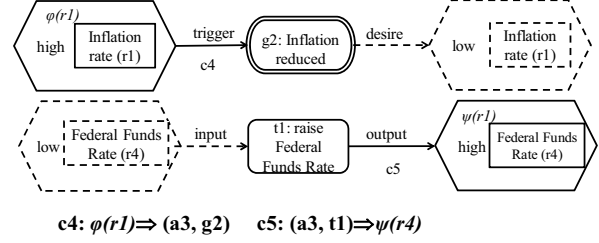


**Figure 4. Intentional Ontology**

Means-ends analysis can be used to connect actors' goals and activities in modeled scenarios. For instance, the goal of reducing inflation (represented as  $g4$ ) can be achieved by carrying out the task of raising the federal fund rate (represented as  $t1$ ), which can be represented as a constraint  $c3$ .

#### 4.2.2. Dynamic ontology

The dynamic ontology defines the economic propositions that will trigger the goals, and defines the economic propositions after carrying out tasks. In other words, the dynamic ontology represents the changing aspect of banking events. For example, as shown in Figure 5, the goal of reducing inflation (represented as  $g2$ ) is triggered by the economic proposition of highInflationRate() (represented as  $\varphi$ ), which can be represented as constraint  $c4: \varphi(r1) \Rightarrow (a3, g2)$ .

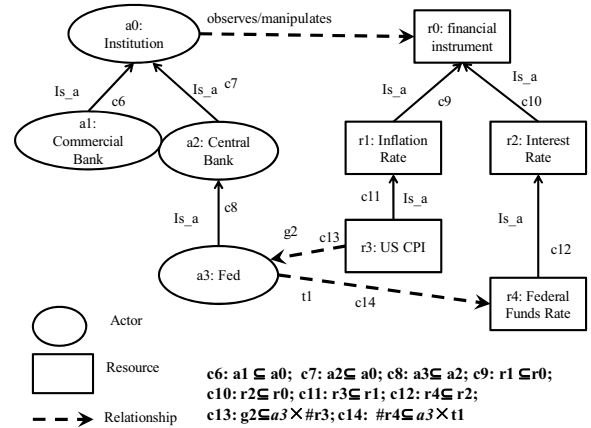


**Figure 5. Dynamic Ontology**

The constraint of “the fed fund rate will surge (represented as  $\psi$ ) after carrying out the task of raise fed fund rate (represented as  $t1$ )” can be written as:  $c5: (a3, t1) \Rightarrow \psi(r4)$ .

#### 4.2.3. Static ontology

The static ontology represents the static aspect of the financial market and defines the basic relation between actors and resources. For instance, as shown in Figure 6, it is the US CPI (represented as  $r3$ ) that triggers the goal of reduce inflation rate ( $g2$ ). And the interest rate that Fed can manipulate (task  $t1$ ) is the Federal Fund Rate (represented as  $r4$ ).



**Figure 6. Static Ontology**

#### 4.2.4. Social ontology

The social ontology describes the social aspects of bank stress testing. In particular, it expresses the knowledge about the social structure and interactions of financial institutions. Three types of intuitional relationships are defined: goal dependency, task dependency, and resource dependency. For example, as the commercial bank has a relation with Federal Reserve with the Federal Funds Rate (resource dependency), the manipulation of “Federal Funds Rate” (represented as  $\#(r4)$ ) will have an impact on commercial banks (represented as  $a1$ ).

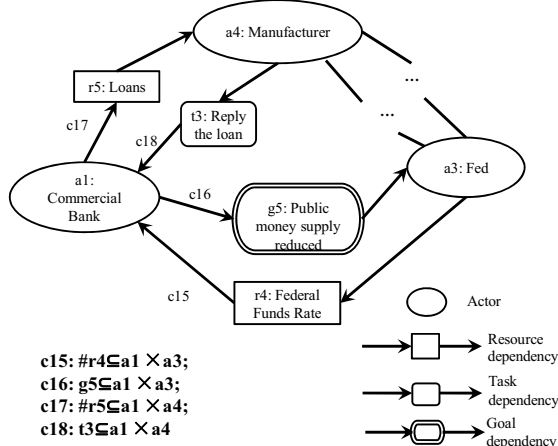


Figure 7. Social Ontology

## 5. Scenario Recommendation

### 5.1. Scenario Recommendation

Scenario recommendation is a process of providing possible but plausible events and activities for user's considerations when user is designing the stress testing scenario. At this section, we will first define the logical system of stress testing scenario recommendation, and then discuss the completeness and soundness of this system.

At any instant of event, there are potentially many different future events in which the scenario can evolve. Thus, to model what possible scenarios may exist and can be recommended to the user, we link different possible scenario to the stress-testing scenario that user is designing with a RECOMMEND-Link. When the stress-testing scenario evolves, we say it is in a new stress-testing event in which new economic propositions hold true and the sets of possible scenarios have altered.

**Definition 8: Scenario recommendation logical system**

A scenario recommendation logical system is defined to be a four-tuple  $M = \langle S, \text{RECOMMEND}, PS, Et \rangle$ , where  $S$  is a set of stress testing scenarios; RECOMMEND is a set of connections that maps the stress-testing scenario to the possible scenarios, i.e.,  $\text{RECOMMEND} \subseteq S \times Et \times PS$ ;  $PS$  is a set of possible scenarios;  $Et$  is the set of stress-testing events that are shared by the stress-testing scenario and the possible scenarios.

Suggestion of economic propositions, denoted by  $\models$ , is given with respect to a scenario recommendation logical system  $M$  and a scenario  $s$ . The expression  $M, s \models \phi$  is read as “the scenario recommendation logical system  $M$  in scenario  $s$  suggests  $\phi$ ”.

Depending on the complexity of scenario, it could be difficult to analyze every possible future event, thus some “exceptional” scenario could be missing. Therefore, scenario recommendation logical system can be evaluated from the perspective of completeness. We define two levels of completeness in terms of whether the model could forecast all future events or the events happened next. More specifically, if the recommendation logic can suggest all of the future plausible economic propositions, it is regarded as strong complete. If the recommendation logic can suggest all the plausible economic propositions in the next event, it is regarded as weak complete.

**Definition 9: Completeness of scenario recommendation logical model**

A scenario recommendation logical system  $M$  is strong complete, iff  $\forall \phi$  that is plausible,  $\exists s \in S, M, s \models \phi$ . A scenario recommendation logical system  $M$  is weak complete, iff  $\forall \phi$  that is plausible,  $\exists s \in S, M, s \models \phi$ .

On another hand, implausibility of economic propositions may exist in a possible scenario. A good scenario recommendation logical system should ensure the plausibility of recommended scenarios in a perspective of soundness. We provide two levels of soundness: strong sound and weak sound. If all the future economic propositions suggested from the scenario recommendation logical system are plausible, the scenario recommendation logical system is regarded as strong sound. If all the economic propositions in the next event recommended from the recommendation logic are plausible, the scenario recommendation logical system is regarded as weak sound.

**Definition 10: Soundness of scenario recommendation logical model**

A scenario recommendation logical model  $M$  is strong sound, iff  $\forall s \in S, M, s \models \phi, \phi$  is plausible. A scenario recommendation logical system  $M$  is weak sound, iff  $\forall s \in S, M, s \models \phi, \phi$  is plausible.

### 5.2. Scenario Recommendation Algorithm

Figure 8 shows an algorithm which aims to construct a scenario recommendation logical system for ontology-based scenario model. It is proven that this logical system is weak complete and weak sound.

**Step 1:** Construct a stress-testing scenario consisting of a single event, and set the event as current event.

**Step 2:** Repeat until none of (a) – (d) below applies

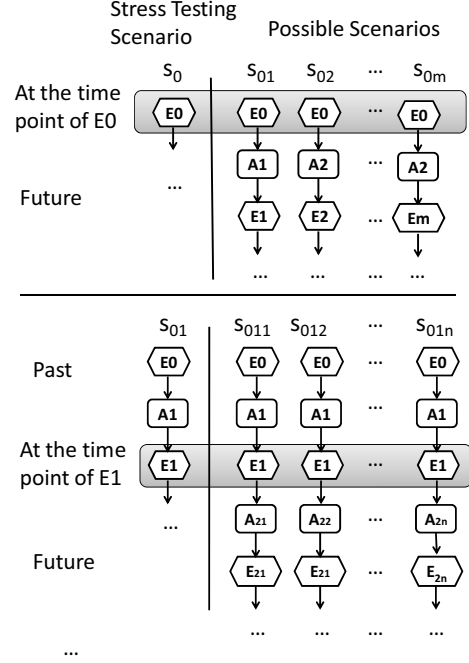
(a). Check static/social ontology and evoke direct/in-direct actors.  
 $\forall c \in O, c.TY = \text{static ontology}, \text{ if } c.P \in R, \text{ then assign } c.H \text{ true at the current event.}$   
 $\forall c \in O, c.TY = \text{social ontology}, \text{ if } c.P \in R, \text{ then assign } c.H \text{ true at the current event}$   
 (b). Check dynamic ontology and trigger goals of evoked actors. Construct new scenarios as a possible scenario with every triggered goals.  
 $\forall c \in O, c.TY = \text{dynamic ontology}, \text{ if } c.P \in P, \text{ then construct a new scenario with assign } c.H \text{ true at the current event.}$   
 (c) Check intentional ontology and assign new activities to the scenario.  
 $\forall c \in O, c.TY = \text{intentional ontology}, \text{ if } c.P \in P, \text{ then construct a new activity and assign } c.H \text{ to the activity.}$   
 (d) Check dynamic ontology and assign new event to the next event of the scenario.  
 $\forall c \in O, c.TY = \text{dynamic ontology}, \text{ if } c.P \in A, \text{ then construct a new event and assign } c.H \text{ to the new event.}$

**Step 3:** User chooses a scenario from the possible scenarios. Then the selected scenario is set as the stress-testing scenario.

**Step 4:** Repeat Step 2 & Step 3, until the user gets the stress-testing scenario wanted.

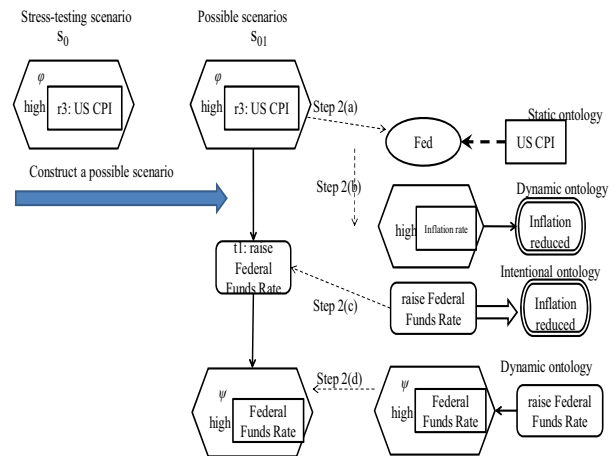
**Figure 8. Scenario Recommendation Algorithm**

The core part of the algorithm is the traversals of the ontologies to seek the possible scenario that predicts a next event for the user to design stress testing scenario. When the user choose a scenario from the possible scenarios, we say the stress testing scenario has evolved to a new event, and a new traversal of the ontologies will generate a new set of possible scenarios for predicting a next event for the new stress testing scenario. Figure 9 shows the process of constructing the scenario recommendation logical system. We first construct a stress testing scenario  $s_0$  by the given starting event  $E_0$ . Then a set of possible scenarios  $\{s_{01}, s_{02}, \dots, s_{0m}\}$  are generated through the inferences in ontologies. Assuming that the user choose scenario  $s_{01}$  as the new stress testing scenario, we say it evolves to the time point of  $E_1$ , and a new set of possible scenarios  $\{s_{011}, s_{012}, \dots, s_{01n}\}$  are recommended to the user.



**Figure 9. Scenario Recommendation**

Figure 10 shows an example of the process to construct a possible scenario from inferences in the ontologies. First, the static and social ontology are checked to see which actor will be evoked, finding the actor “Fed” keep observing the changing status of US CPI. The dynamic ontology is checked then in step 2(b), and because it is in an event consisting of economic proposition on high inflation rate  $\phi(r1)$ , the head of constraint  $c4$  (as shown in Figure 5) will be assigned true in the current event. In step 2(c), the activity of raise the fed fund rate will be executed (constraint  $c3$  in Figure 4). A new event high fed fund rate will then be assigned to the scenario according to constraint  $c5$  (as shown in Figure 5).



**Figure 10. Construct a possible scenario**



We propose that the scenario recommendation logical system constructed by our algorithm is weak complete and weak sound.

**Theorem 1:** The scenario recommendation logical system  $M$  is weak complete.

**Proof:** according to Definition 10,  $\forall \phi$  that is plausible,  $\exists a \in \text{Actor}, \exists t \in \text{Task}, \exists g \in \text{Goal}, (a, t) \Rightarrow \phi(r), (a, g) \Rightarrow (a, t)$ . Thus, a constraint will be found in the intentional ontology defining the relation between goal and task, and a constraint will be found in the dynamic ontology defining the task and  $\phi$ , the goal and the current event. If there is a next event stating  $\phi$ , then the proposition have been proved.

**Theorem 2:** The scenario recommendation logical system  $M$  is weak sound.

**Proof:** According to step 3, 4, 5, the next event will be constructed only when there is a goal of the actor to execute the task. In other words, some actor has the capability to manipulate the economic resources into the economic proposition and the actor has an intention to do so. Thus, the economic proposition derived from the next event of scenario recommendation logical system  $M$  is plausible. Therefore,  $M$  is weak sound.

## 6. Discussion

The proposed scenario modeling approach provides stress testing designers the capabilities to model

exceptional but plausible financial crisis scenarios. Figure 11 shows an example how the user can model a stress testing scenario using the proposed BESST approach. Figure 12 summarizes the ontologies used in the example.

In this example, when the user wants to model an activity after an event of “inflation”, several possible activities, (e.g., “raise interest rate”, “fix exchange rate” and “control wage and price”) are suggested based on the intentional ontology c1 and c2. After the user chooses “raise interest rate” as the stress-testing activity, a new event “interest rate surges” can be inferred from the dynamic ontology c3. If the user wants to have “manufacturer reduces production” as the next activity, the ontologies will also have a process of recommending other possible activities. First, the social ontologies will suggest that both the real estate investor and manufacturer are dependent on loans from commercial banks, and the rates of loans is determined by interest rates as defined in static ontology. However, the event of “interest rate surges” will trigger real estate investor’s goal of “pay as little interests as possible” and carry out a task of “reduce real estate investment.” Thus, the activity of “decrease real estate investment” is also possible. If the user chooses the activity of “manufacturers reduce production”, which will result in a decrease in employment.

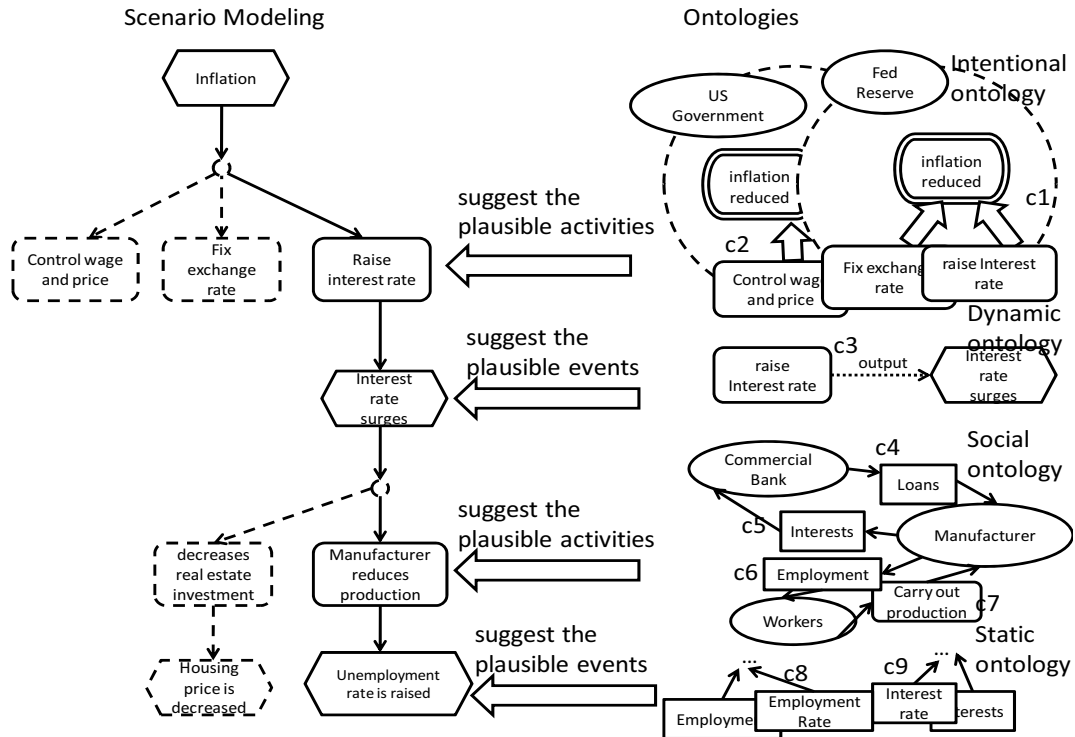


Figure 11. The role of ontologies in scenario modeling

c1: (Intentional Ontology) Fed reserve has a goal to reduce the inflation, which can be achieved by either raise interest rate or fix exchange rate.  
 c2: (Intentional Ontology) US Government has a goal to reduce the inflation, which can be achieved by controlling the wage and price.  
 c3: (Dynamic Ontology) Carrying out the task of raise interest rate results in interest rate surge.  
 c4: (Social Ontology) Manufacturer relies on loans from commercial banks.  
 c5: (Social Ontology) Manufacturer needs to pay interest for the loans from commercial banks.  
 c6: (Social Ontology) Workers relies on employment from manufacturer.  
 c7: (Social Ontology) Manufacturer depends on workers to carry out the production.  
 c8: (Static Ontology) The employment rate has a data-property relationship with employment.  
 c9: (static Ontology) The interests pay for commercial banks has a data-property relationship with interest rate.

**Figure 12. Key Ontological Constraints**

## 7. Conclusion

The proposed ontology-based stress testing approach – BESST – has several contributions. First, it enables the stress testing stakeholders to model dynamic processes of risk events that cannot be captured by existing probability-based stress testing methods. Second, the Ontology-supported scenario model in BESST provides formal definitions of various stress testing elements such as bank activities and economic propositions, effectively enabling logical deductions of possible risk events in various scenarios. Third, such a logic deduction function can then recommends possible sequences of risk events to stress testing scenario designers to support their scenario modeling activities.

The major limitation of our study is that currently BESST assumes a stress testing scenario is a single sequence of events and activities. The parallel occurrences of events are not modeled. Therefore, our future work will focus on improving BESST to allow the modeling of multiple risk event processes. Second, we plan to develop a prototype of scenario recommendation system that can support real-world bank stress testing scenario design

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